CLAIMS

1. A power transmission system for regulating the delivery of power to a drive shaft, said power transmission system comprising:

an engine having an output shaft;

a pair of planetary trains operatively coupled between said output shaft and said drive shaft for transmitting power output from said engine to said drive shaft, each of said planetary trains including a sun member, a ring member, a set of planet members, and a planet carrier;

a first electric machine linked with at least said one member of a first planetary train in said pair of planetary trains for receiving and transmitting power to and from said drive shaft;

a second electric machine linked with said one member of a second planetary train in said pair of planetary trains for receiving and transmitting power to and from said drive shaft;

a set of torque transfer components operatively coupled to said pair of planetary trains, said set of torque transfer components including a clutch for selectively coupling a member of said first planetary train to a member of said second planetary train, and a brake for selectively coupling said a member of said second planetary train to a fixed member of the power transmission system;

an engine control unit configured to provide an engine torque responsive to a target torque level established based on a performance objective;

a power control unit operatively coupled to said first and second electric machines, said power control unit configured to control a flow of electric power to and

from each of said electric machines to regulate a magnitude of delivered power to the drive shaft, and said power control unit further configured to control of said at least one set of torque transfer components.

2. The power transmission system of Claim 1 wherein said first and second electric machines each have a power rating P_v of :

$$P_v \geq \frac{\left(\sqrt{\frac{SR_2}{SR_1}(1+\psi)}-1\right)^2}{\frac{SR_2}{SR_1}-1} P_{in}$$

where P_{in} is power delivered to the input of said power transmission system;

where SR_1 is the output-to-input speed ratio at which said first electric machine has a zero rotational speed;

where SR_2 is the output-to-input speed ratio at which said second electric machine has a zero rotational speed; and

where ψ is a ratio of electric input power to said first and second electric machines to mechanical input power at said engine output shaft.

3. The power transmission system of Claim 1 wherein said power control unit is configured to select a control structure for said first and second electric machines responsive to a speed ratio between said drive shaft and said engine output shaft.

4. The power transmission system of Claim 3 wherein said power control unit is configured to control one of said first and second electric machines to provide torque to regulate said speed ratio.

5. The power transmission system of Claim 3 wherein said power control unit is configured to control one of said first and second electric machines to provide torque to balance power in said pair of planetary trains.

6. The power transmission system of Claim 1 wherein said power control unit is configured to selectively control said at least one set of torque transfer components responsive to a speed ratio between said drive shaft and said engine output shaft.

7. The power transmission system of Claim 6 wherein said power control unit is configured to control said at least one set of torque transfer components to selectively couple two or more components of said pair of planetary trains in an output power-split configuration.

8. The power transmission system of Claim 6 wherein said power control unit is configured to control said at least one set of torque transfer components to selectively couple two or more components of said pair of planetary trains in an compound power-split configuration.

9. The power transmission system of Claim 6 wherein said power control unit is configured to control said at least one set of torque transfer components to alter one or more couplings between said pair of planetary trains between an output power-split configuration and a compound power-split configuration at a node point where a rotational speed of at least one of said first and second electric machines is substantially zero.

10. The power transmission system of Claim 1 further including an energy storage device operatively coupled to said first and second electric machines; and

wherein said power control unit is operatively coupled to said energy storage device to regulate a flow of electric energy between said energy storage device, said first electric machine, and said second electric machine.

11. The power transmission system of Claim 10 wherein said engine control unit is configured to shut off said engine responsive to a predetermined set of operating conditions; and

wherein said power control unit is further configured to

control said torque transfer components to decouple said first and second planetary trains responsive to said predetermined set of operating conditions; and to regulate a flow of electric power from said energy storage device to at least one of said first and second electric machines, wherein said electric machine provides power to said drive shaft through said second planetary train.

12. The power transmission system of Claim 3 wherein said power control unit is configured responsive to said speed ratio:

(a) at or below a first node point to regulate torque from said first electric machine and said second electric machine utilizing a first control regime; and

(b) greater than said first node point to regulate torque from said first electric machine and said second electric machine utilizing a second control regime.

13. The power transmission system of Claim 12 wherein said power control unit is further configured responsive to said speed ratio greater than a switch point to regulate torque from said second electric machine and said first electric machine utilizing a third control regime.

14. The power transmission system of Claim 13 wherein said power control unit is further configured to optionally utilize said third control regime in place of said second control regime when said speed ratio is greater than said first node point to regulate torque from said first electric machine and said second electric machine.

15. The power transmission system of Claim 12 wherein said power control unit is configured responsive to said speed ratio at or below said first node point to regulate torque from said first electric machine to:

$$T_{E1} = \frac{T_{R1}}{K_1} + \varphi_{SGI}\left(\omega_e^* - \omega_e\right)$$

and the power from said second electric machine to:

$$P_{E2} = -P_{E1} + P_{pto\_e}$$

where

T_{R1} is the input torque to the ring member of the first planetary train;

K_1 is the planetary ratio of the first planetary train;

$\varphi_{SGI}(\omega_e^* - \omega_e)$ is a feedback function of engine speed error;

P_{E1} is the electrical power from the first electric machine; and

P_{pto_e} is the electrical power taken off from said engine and said pair of planetary trains.

16. The power transmission system of Claim 12 wherein said power control unit is configured responsive to said speed ratio greater than said first node point to regulate torque from said first electric machine to:

$$T_{E1} = \left(\frac{K_1 K_2}{K_2 + 1} \cdot \frac{1}{SR_{o-i}} + \frac{1 - K_1 K_2}{K_2 + 1} \right) \frac{T_{R1}}{K_1} - \frac{K_2}{K_2 + 1} \cdot \frac{P_{pto\_e}}{\omega_d} + \varphi_{SGii}\left(\omega_e^* - \omega_e\right)$$

and the power from said second electric machine to:

$$P_{E2} = -P_{E1} + P_{pto\_e}$$

where

T_{R1} is the input torque to the ring member of the first planetary train;

K_1 is the planetary ratio of the first planetary train;

K_2 is the planetary ratio of the second planetary train;

$SR_{o\text{-}I}$ is the speed ratio;

$\varphi_{SGII}(\omega_e^* - \omega_e)$ is a feedback function of engine speed error;

P_{E1} is the electrical power from the first electric machine; and

P_{pto_e} is the electrical power taken off from said engine and said pair of planetary trains.

17. The power transmission system of Claim 12 wherein said power control unit is configured responsive to said speed ratio greater than said first node point to regulate torque from said second electric machine to:

$$T_{E2} = \left(\frac{K_1}{K_2 + 1} \cdot \frac{1}{SR_{o-i}} - \frac{K_1 + 1}{K_2 + 1} \right) \frac{T_{R1}}{K_1} - \frac{1}{K_2 + 1} \cdot \frac{P_{pto\_e}}{\omega_d} + \varphi_{SGIIi}\left(\omega_e^* - \omega_e\right)$$

and the power from said first electric machine to:

$$P_{E1} = -P_{E2} + P_{pto\_e}$$

where

T_{R1} is the input torque to the ring member of the first planetary train;

K_1 is the planetary ratio of the first planetary train;

K_2 is the planetary ratio of the second planetary train;

$SR_{o\text{-}I}$ is the speed ratio;

ω_d is the drive shaft speed;

$\varphi_{SGIII}(\omega_e^* - \omega_e)$ is a feedback function of engine speed error;

P_{E2} is the electrical power from the second electric machine; and

P_{pto_e} is the electrical power taken off from said engine and said pair of planetary trains.

18. The power transmission system of Claim 12 wherein said power control unit is configured responsive to said speed ratio:

(a) greater than said first node point and below a switch point less than a second said node point to regulate torque from said first electric machine to

$$T_{E1} = \left(\frac{K_1 K_2}{K_2 + 1} \cdot \frac{1}{SR_{o-i}} + \frac{1 - K_1 K_2}{K_2 + 1} \right) \frac{T_{R1}}{K_1} - \frac{K_2}{K_2 + 1} \cdot \frac{P_{pto\_e}}{\omega_d} + \varphi_{SGii}\left(\omega_e^* - \omega_e\right)$$

and to regulate power from said second electric machine to:

$$P_{E2} = -P_{E1} + P_{pto\_e}$$

where

T_{R1} is the input torque to the ring member of the first planetary train;

K_1 is the planetary ratio of the first planetary train;

K_2 is the planetary ratio of the second planetary train;

$SR_{o\text{-}I}$ is the speed ratio;

$\varphi_{SGII}(\omega_e^* - \omega_e)$ is a feedback function of engine speed error;

P_{E1} is the electrical power from said first electric machine; and

P_{pto_e} is the electrical power taken off from said engine and said pair of planetary trains;

(b) at or greater than said switch point to regulate torque from said second electric machine to

$$T_{E2} = \left(\frac{K_1}{K_2+1} \cdot \frac{1}{SR_{o-i}} - \frac{K_1+1}{K_2+1} \right) \frac{T_{R1}}{K_1} - \frac{1}{K_2+1} \cdot \frac{P_{pto\_e}}{\omega_d} + \varphi_{SGiIi} \left(\omega_e^* - \omega_e \right)$$

and the power from said first electric machine to:

$$P_{E1} = -P_{E2} + P_{pto\_e}$$

where

T_{R1} is the input torque to the ring member of the first planetary train;

K_1 is the planetary ratio of the first planetary train;

K_2 is the planetary ratio of the second planetary train;

$SR_{o\text{-}I}$ is the speed ratio;

ω_d is the drive shaft speed;

$\varphi_{SGIII} (\omega_e^* - \omega_e)$ is a feedback function of engine speed error;

P_{E2} is the electrical power from said second electric machine; and

P_{pto_e} is the electrical power taken off from said engine and said pair of planetary trains.

19. The power transmission system of Claim 1 wherein said power control unit is further configured to control said at least one set of torque transfer components to decouple said first and second planetary trains, to drive said first electric machine from

said engine through said first planetary train to generate electric power, and to drive said drive shaft in reverse operation from said second electric machine through said second planetary train; and

wherein said power control unit is further configured to regulate a flow of electric power from said first electric machine to said second electric machine.

20. The power transmission system of Claim 19 wherein said first planetary train is configured to amplify a rotational speed between said output shaft of said engine and said first electric machine; and

wherein said second planetary train is configured to reduce a rotational speed between said second electric machine and said drive shaft.

21. The power transmission system of Claim 1 wherein said engine control unit and power control unit are configured for hybrid mode operation.

22. The power transmission system of Claim 1 wherein said engine control unit and power control unit are configured for non-hybrid mode operation.

23. The power transmission system of Claim 1 wherein said engine control unit and power control unit are configured for electric-only operation.

24. The power transmission system of Claim 1 wherein said engine control unit and power control unit are configured for series hybrid mode operation.

25. A method for series hybrid operation in a power transmission system including an engine having an output shaft, a pair of planetary units between the engine output shaft and an output drive shaft, each planetary unit having ring member located around a sun member, planet members located between the sun and ring members, and a carrier member coupled with the planets and providing axes about which the

planet members rotate, one of the members of the first planetary unit engageable with one of the members of the second planetary unit to form a first compound member branch, another of the members of the first unit engageable with another of the members of the second planetary unit to form a second compound branch, a first electric machine coupled to the sun member of the first planetary unit, and a second electric machine coupled to the sun member of the second planetary unit, a power control unit coupled to the first and second electric machines, the method comprising:

decoupling said first and second planetary trains from each other;

configuring said first planetary train as a speed increaser;

driving said first electric machine from said engine output shaft through said first planetary train to generate electrical power;

configuring said second planetary train as a speed reducer;

delivering said electrical power from said first electric machine to said second electric machine;

driving said output drive shaft from said second electric machine through said secondary planetary train; and

regulating said generation and delivery of electrical power from said first electric machine to said second electric machine to control said output drive shaft rotational speed.

26. A method for power regulation in a power transmission system including an engine having an output shaft, a pair of planetary units between the engine output shaft and an output drive shaft, each planetary unit having ring member located around a sun member, planet members located between the sun and ring members, and a

carrier member coupled with the planets and providing axes about which the planet members rotate, at least one of the members of the first planetary unit engagable with one of the members of the second planetary unit to form a compound member branch, , a first electric machine coupled to one member of the first planetary unit, and a second electric machine coupled to one member of the second planetary unit, a power control unit coupled to the first and second electric machines, the method comprising:

identifying the output drive shaft rotational speed and driver inputs;

calculating engine output utilizing said output drive shaft rotational speed and at least one driver input;

determining a engine operating point based on a selected performance objective;

calculating a speed ratio between said output drive shaft and said engine output shaft;

selecting an operating regime for said power transmission system based upon said calculated speed ratio;

selecting a control routine for each of said first and second electric machines based upon said calculated speed ratio;

controlling one of said electric machines to provide torque to regulate said engine rotational speed based upon said operating regime and control routines;

controlling a second of said electric machines to provide torque to balance power in said first and second planetary units based upon said operating regime and control routines; and

regulating the engine to achieve a desired engine output torque based on a selected performance objective.

27. The method for power regulation of Claim 26 wherein the step of selecting a control routine for each of said electric machines is responsive to said speed ratio being:

(a) at or below a first node point, to select a first set of control routines;

(b) greater than said first node to select a second set of control routines; and

(c) greater than a switch point to select a third set of control routines.

28. The method for power regulation of Claim 27 wherein said first set of control routines regulates torque from said first electric machine to:

$$T_{E1} = \frac{T_{R1}}{K_1} + \varphi_{SGI}\left(\omega_e^* - \omega_e\right)$$

and power from said second electric machine to:

$$P_{E2} = -P_{E1} + P_{pto\_e}$$

where

T_{R1} is the input torque to the ring member of the first planetary train;

K_1 is the planetary ratio of the first planetary train;

$\varphi_{SGI}(\omega_e^* - \omega_e)$ is a feedback function of engine speed error;

P_{E1} is the electrical power from the first electric machine; and

P_{pto_e} is the electrical power taken off from said engine and said pair of planetary trains.

29. The method for power regulation of Claim 27 wherein said second set of control routines regulates torque from said first electric machine to:

$$T_{E1} = \left(\frac{K_1 K_2}{K_2 + 1} \cdot \frac{1}{SR_{o-i}} + \frac{1 - K_1 K_2}{K_2 + 1} \right) \frac{T_{R1}}{K_1} - \frac{K_2}{K_2 + 1} \cdot \frac{P_{pto\_e}}{\omega_d} + \varphi_{SGII}\left(\omega_e^* - \omega_e\right)$$

and power from said second electric machine to:

$$P_{E2} = -P_{E1} + P_{pto\_e}$$

where

T_{R1} is the input torque to the ring member of the first planetary train;

K_1 is the planetary ratio of the first planetary train;

K_2 is the planetary ratio of the second planetary train;

$SR_{o\text{-}I}$ is the speed ratio;

$\varphi_{SGII}(\omega_e^* - \omega_e)$ is a feedback function of engine speed error;

P_{E1} is the electrical power from the first electric machine; and

P_{pto_e} is the electrical power taken off from said engine and said pair of planetary trains.

30. The method for power regulation of Claim 27 wherein said third set of control routines regulates torque from said first electric machine to:

$$T_{E2} = \left(\frac{K_1}{K_2 + 1} \cdot \frac{1}{SR_{o-i}} - \frac{K_1 + 1}{K_2 + 1} \right) \frac{T_{R1}}{K_1} - \frac{1}{K_2 + 1} \cdot \frac{P_{pto\_e}}{\omega_d} + \varphi_{SGIII}\left(\omega_e^* - \omega_e\right)$$

and power from said first electric machine to:

$$P_{E1} = -P_{E2} + P_{pto\_e}$$

where

T_{R1} is the input torque to the ring member of the first planetary train;

K_1 is the planetary ratio of the first planetary train;

K_2 is the planetary ratio of the second planetary train;

$SR_{o\text{-}I}$ is the speed ratio;

ω_d is the drive shaft speed;

$\varphi_{SGIII}(\omega_e^* - \omega_e)$ is a feedback function of engine speed error;

P_{E2} is the electrical power from the second electric machine; and

P_{pto_e} is the electrical power taken off from said engine and said pair of planetary trains.

31. The method for power regulation of Claim 26 wherein the step of selecting an operating regime for said power transmission system is responsive to said calculated speed ratio being:

(a) at or below a first node point, to select an output-power split operating regime and to disengage the second compound branch members; and

(b) greater than said first node point to select a compound power-split operating regime and to engage the second compound branch members.

32. The method of Claim 26 for power regulation in a power transmission system wherein a low-speed hybrid operating regime is selected further including the steps of:

decoupling said first and second planetary units;

regulating said engine output torque to zero;

delivering electrical power to said second electric machine from an energy storage device; and

controlling said second electric machine to provide torque to said output drive shaft through said second planetary unit.